SYSTEM AND METHOD OF HALFTONING FOR MULTI-PASS RENDERING

Background

[001] The present invention relates to a system and method of halftoning for multi-pass rendering, and more particularly to a system and method of halftoning for reducing the effects of inter-pass mis-registration in multi-pass printing.

[002] With the advent of inexpensive digital color printers, methods and systems of digital halftoning have become increasingly important. It is well understood that most digital printers operate in a binary mode, i.e., for each tonal separation, a corresponding spot is either printed or not printed at a specified location or pixel. Digital halftoning controls the printing of tonal spots, where spatially averaging the printed spots of one or more tonal separations provides the illusion of the required continuous contone.

[003] A common halftone technique is screening, which compares the required continuous tone level of each pixel for each separation with one of several predetermined threshold levels. The predetermined threshold levels are stored in a two-dimensional threshold array called a halftone screen. If, in any given region of the image, the required tone level is darker than the threshold halftone level, the pixel is turned on and printed. These pixels can be referred to as black pixels, even though they may be printed in color. Pixels not turned on are not printed and can be referred to as white pixels. It is understood in the art that the distribution of black pixels depends on the design of the halftone screen.

[004] Some known inkjet printers print with multiple passes. With multi-pass printing, the image

pixels are spatially partitioned into sets, or partitions, and a different partition is printed in each pass. Multi-pass printing can allow for better ink drying and can reduce the visibility of print head signature caused by deviations in the size and positioning of the printed dots.

[005] A common multi-pass printer is a two-pass printer, though multi-pass printers can use any suitable number of passes. Two-pass printers print some of the black pixels in the first pass and the rest of the black pixels in the second pass. Often, one pass is printed in the forward direction of head traversal and the other in the reverse direction.

[006] If the alignment or registration between the passes is near perfect, the graininess of the resulting images is largely unchanged in comparison with a printer that prints the entire image in a single pass. However, if there is mis-registration between the two passes the partitions can "beat" with each other to produce undesired textures that result in considerably increased graininess in the printed image.

[007] Mis-registration in inkjet printers arises from mechanical positioning errors between the passes. Increasing the precision in the mechanical positioning can mitigate the problem of mis-registration. However, this solution can be costly due to the tight tolerances required particularly at high resolutions.

[008] Mis-registration that is identical from page to page over the life of the printer can be detected *a priori* and compensated for electronically. However, electronic compensation of each individual printer also adds cost to printers. Also, electronic compensation cannot correct registration errors under half a pixel without excessive computation.

[009] It is desirable to provide halftone screens, which reduce the effects of mis-registration in multi-pass printers in a highly accurate yet cost effective manner.

Summary of the Invention

[010] A system and method for halftoning for reducing the effects of mis-registration in multi-pass printing. The system and method for halftoning provide increased robustness to inter-pass registration errors by primarily using the pixels from a single partition for printing in the highlight regions where graininess is the biggest problem. By concentrating the minority black pixels in a single pass, the systems and methods of the invention ensure that the gap between the minority pixels is not affected by inter-pass mis-registration errors. A similar benefit is also obtained in the shadow regions by similarly restricting a substantial majority of the minority white pixels to a single pass.

[011] The method of halftoning for multi-pass rendering includes restricting a substantial majority of the pixels turned on to render a tone to the minimum number of passes required to produce the tone. The substantial majority can be approximately 75% or more, or more preferably approximately 90% or more, of the pixels turned on to render a tone.

[012] The halftoning method can include generating a stochastic screen pixel turn-on sequence and re-ordering the turn-on sequence. The halftoning method can also use error diffusion, adding a zero mean bias signal to either the image input pixels or the threshold values. The halftoning method is applicable to color or black and white rendering.

[013] The system of halftoning for multi-pass rendering of an image having pixels, wherein different pixels are rendered in each pass, includes means for restricting a substantial majority of the pixels turned on to render a tone to the minimum number of passes required to produce the tone.

Brief Description of the Drawings

[014] The drawings are only for purposes of illustrating preferred embodiments and are not to be construed as limiting the invention. The invention may take form in various components and arrangements of components, and in various steps and arrangements of steps, preferred embodiments of which will be illustrated in the accompanying drawings wherein:

[015] FIG. 1 is a diagram illustrating a checkerboard partition;

[016] FIG. 2 is a diagram illustrating a stochastic screen pixel turn-on sequence;

[017] FIG. 3 is a diagram illustrating the stochastic screen pixel turn-on sequence of FIG. 2 partitioned into the checkerboard partition illustrated in FIG. 1;

[018] FIG. 4 is a diagram illustrating the step of re-ordering the pixel turn-on sequence;

[019] FIG. 5 is a diagram of the re-ordered pixel turn-on sequence;

[020] FIG. 6 is a diagram illustrating the output of a stochastic halftone screen;

[021] FIG. 7 is a diagram illustrating rendered pixels in accordance with the stochastic halftone screen of FIG. 6;

[022] FIG. 8 diagram illustrating rendered pixels in accordance with a stochastic halftone screen generated using the pixel turn-on sequence of FIG. 2;

[023] FIG. 9 is a diagram illustrating the zero mean bias signals arranged in the checkerboard partition arrangement shown in FIG. 1;

[024] FIG. 10 is a block diagram illustrating the method of error diffusion in accordance with the invention;

[025] FIG. 11 is a block diagram illustrating an alternate embodiment of the method of error diffusion in accordance with the invention;

[026] FIG. 12 is a diagram illustrating the threshold values used in the alternate embodiment shown in FIG. 10; and

[027] FIG. 13 is a diagram illustrating a system of halftoning for multi-pass rendering in accordance with the invention.

Detailed Description of the Invention

[028] It is to be understood that the specific devices and processes illustrated in the attached drawings, and described in the following specification are simply exemplary embodiments of the inventive concepts defined in the appended claims. Hence, specific examples and characteristics relating to the embodiments disclosed herein are not to be considered as limiting, unless the claims expressly state otherwise.

[029] For the purposes of example the invention is described for two-pass printing, although it should be noted the invention is applicable to any multi-pass printing scheme. Further, a "checkerboard" two-pass partition is used, as shown generally at **10** in FIG. 1. In the checkerboard partition **10**, each cross-hatched square **a**

corresponds to a pixel in a first partition $S1$ and each white square **b** corresponds to a pixel in a second partition $S2$. However, the ideas and algorithms developed are equally applicable to other known partitions, including but not limited to alternate line partitions using even and odd rows/columns, stochastic partitions, or any other suitable known partitions.

[030] A first embodiment of the invention uses stochastic screening similar to the method of generating a stochastic halftoning screen as taught in U.S. Patents 5,673,121 and 6,014,500 to Wang which are hereby incorporated herein by reference. The method of halftoning as described below in relation to stochastic screening can include generating the stochastic screen and applying the screen to render an image.

[031] The design of the stochastic screen S is a mathematical optimization process having a single-valued merit function M(S), an example of which is disclosed in the above referenced U.S. Patent 5,673,121. The screen S is partitioned into two subsets: $S1$ is defined by all pixels, which are printed in the first pass (including black pixels which are turned on, and white pixels which are not turned on), and $S2$ is defined by all the pixels which are printed in the second pass (including black pixels which are turned on, and white pixels which are not turned on). For the checkerboard partition described above, the pixels can be classified as belonging to the two partitions using the coordinates of columns and rows, i and j, and the mathematical rule

$$
\begin{aligned}
&p(i,j) \in S1, \quad if(i+j)\%2 = 0; \\
&p(i,j) \in S2, \quad if(i+j)\%2 = 1; \\
&S = S1 + S2.
\end{aligned}
$$

[032] A new merit function, $\widetilde{M}(S)$, is used which is composed of three parts:

$$\widetilde{M}(S) = M(S) + w_1 * M(S1) + w_2 * M(S2),$$

where $M(\,)$ is a merit function similar to the merit function for a single screen, and w_1 and w_2 are weighting factors which control the relative importance of textures in partitions *S1* and *S2*, respectively, in relation to the overall textures.

[033] In the example provided, $w_1 \approx 3$ and $w_2 \approx 3$, although these weighting factors can each have a different value, and the values can be in the range of approximately 2 to 100. The higher weighting for the *S1* and *S2* partitions in the merit function ensure that the textures obtained from the process of partitioning the original turn-on sequence and re-arranging it as described below produces pleasing halftone textures.

[034] Optimizing the merit function produces a pixel turn-on sequence for the entire stochastic screen *S*. The pixel turn-on sequence, also be referred to as a stochastic screen pixel turn-on sequence, is a pixel turn-on sequence used for generating a stochastic halftone screen *S*. The pixel turn-on sequence gives the sequence for turning on successive pixels in *S*, as will be described below, such that the pleasing appearance is maintained as each successive pixel is turned on and thus printed.

[035] Referring to FIG. 2, the pixel turn-on sequence generated in accordance with the first embodiment is shown generally at **20**. The pixel turn-on sequence **20** is shown as a 4x4 screen **22**, having sixteen screen

elements **24** each corresponding to a pixel for an input image with 17 possible input levels, ranging from 0 through **16.** Each screen element **24** includes a turn-on sequence value **26** representing the sequence order in which the pixel is turned on, from the lowest to the highest value, when halftoning a constant input image, or portion thereof. This example is for purposes of illustration only and the pixel turn-on sequence can be optimized further by known methods. Also, typical stochastic screens are usually larger than 4x4.

[036] Next, the turn-on sequence **20** is partitioned or split up into partitions. For this example, halftoning for two-pass rendering using a checkerboard partition, the partitioned turn-on sequence is shown generally at **28** in FIG. 3. The turn-on sequence values **26** are shown partitioned into a first partition *S*1 occupying screen elements **24a** and a second partition *S*2 occupying screen elements **24b**.

[037] Referring to FIGS. 4 and 5, the partitioned turn-on sequence **28** is then re-ordered by changing the pixel turn-on sequence values **26** of the screen elements **24** (pixels) to fill one of the partitions, here *S*1, with the lowest turn-on values **26** in the entire turn-on sequence before filling the second partition *S*2 with the highest turn-on values **26** in the turn-on sequence. In this example, the pixel turn-on sequence in *S*1 is re-ordered, using all the pixel turn-on sequence values in *S* so that the turn-on sequence values **26** having the lowest values, 1-8 in this example, reside in partition *S*1 and the turn-on sequence values **26** having the highest values, 9-16 in this example, reside in partition *S*2.

[038] The re-ordering step can be accomplished in any suitable manner. One example of the

re-ordering step, which should not be considered limiting, includes: a) replacing the lowest stochastic screen pixel turn-on value before re-ordering contained in one partition with a replacement value which is the lowest stochastic screen pixel turn-on sequence value of all partitions of the screen; b) replacing the next lowest stochastic screen pixel turn-on value in the one partition with a replacement value which is the next lowest stochastic screen pixel turn-on sequence value of all partitions of the screen; c) repeating step b) until the one partition is filled with the lowest stochastic screen pixel turn-on sequence values of all partitions of the screen; and d) repeating steps a) through c) to re-order each of the other partitions in turn with the remaining unused replacement values.

[039] Thus, as illustrated in FIG. 4, the lowest turn-on value of the entire screen *S* is placed in the screen element **24a** of *S*1 having the lowest turn-on value **26** before re-ordering. In the example provided, the screen element **24a** of *S*1 having the lowest value before re-ordering contains a 1, so this value is not changed. The *S*1 screen element **24a** having the next lowest value before re-ordering contains a **2**, so again this value is not changed. The turn-on value **26** of the screen element in *S*1 having the next lowest value before re-ordering, a 5, is changed to a 3. The turn-on value **26** of the screen element in *S*1 having the next lowest value, a 6, is changed to a 4. This is continued until screen *S*1 contains the lowest turn-on values, 1-8.

[040] This process is repeated for the second partition *S*2. The turn-on value **26** of the *S*2 screen element **24b** having the lowest value before re-ordering, a 3, is changed to the next lowest turn-on value in the sequence, that is a 9. The turn-on value of the *S*2

screen element **24b** having the next lowest value, a 4, is changed to next lowest turn-on value in the sequence, a 10. This is continued until screen *S*2 contains the highest turn-on values 9-16. The resulting re-ordered turn-on sequence **30** is illustrated in FIG. 5.

[041] The re-ordering step can also be accomplished by: a) obtaining a subsequence for each partition by arranging the pixels within the partition in increasing order of turn-on sequence values, b) concatenating the subsequences for the different partitions (in any order) to form a single sequence, and c) renumbering the resulting single sequence in increasing order of turn-on values to obtain the new turn-on sequence.

[042] Referring to FIG. 6, the re-ordered pixel turn-on sequence **30** is then converted to threshold values shown at **34** in a known manner to form a stochastic halftone screen **36**. The threshold values **34** output from the halftone screen **36** includes a number of different values corresponding to the bit depth of the input signal.

[043] For the present example, in order to obtain a halftone screen **36** with 3-threshold levels for halftoning a 2-bit input signal from the re-ordered pixel turn-on sequence **30** illustrated in FIG. 5, the pixel turn-on sequence **30** is converted to threshold values between 1 and 3 by mapping the pixels to the thresholds according to the pixel turn-on sequence. The pixels corresponding to values 1 through a number, such as h1, are mapped to threshold value 1, pixels corresponding to values h1+1 through h2 are mapped to threshold value 2, and pixels corresponding to values h2+1 through 16 are mapped to threshold value 3.

[044] A simple illustrative mapping is obtained by spacing the values h1, h2, and h3 substantially linearly so that:

h1 = round(16/3)= 5

h2 = round(16*2/3)= 11

h3 = round(16*3/3)= 16

However, any other suitable nonlinear spacings of the values **34** can also be used.

[045] The tonal intensity value of the input image will then be used to determine which pixels are rendered, that is actually turned on resulting in a printed output, and those which remain off and thus are not printed. For the purpose of this example, using a 2-bit image having a constant tonal intensity value of 25%, or 1 out of 0-3, only the 1's are turned on, or rendered, resulting in black pixels represented by the cross-hatched squares **40** in the halftone output pattern **42** illustrated in FIG. 7. The black pixels **40** occupy *S*1 screen elements **24a** and are printed in only one pass making the rendered pattern less sensitive to inter-pass mis-registration than known methods of halftoning.

[046] By providing the re-ordered turn-on sequence **30** in accordance with the invention, the minority pixels in the highlights, that is the pixels turned on or printed, will be restricted to a minimum number of partitions or printer passes. Also, the minority pixels in the shadows, that is the pixels not turned on or not printed, are restricted to a minimum number of partitions or printer passes. The halftoning method described above reduces the sensitivity of the highlights and shadows, where graininess and visibility is a significant problem, to mis-registration between passes. Stated another way, the re-ordered turn-on sequence **30** restricts the pixels

turned on to render a tone to the minimum number of partitions, and thus passes, required to produce the tone.

[047] The invention can be extended to any desired number of partitions or passes, such as for example, 4 partitions for four-pass printing. A stochastic screen pixel turn-on sequence is generated using any known method of stochastic screening for four-pass rendering. The pixel turn-on sequence is partitioned into 4 partitions and then re-ordered to restrict a substantial majority of the pixels turned on to render a tone to the minimum number of passes to produce the tone. After re-ordering, the first partition *S1* contains the lowest pixel turn-on values. The second partition, *S2* contains the next lowest pixel turn-on values, the third partition, *S3* contains the next lowest pixel turn-on values, and the fourth partition *S4* contains the highest pixel turn on values.

[048] In this example of halftoning for four-pass printing, if an input image has a tonal intensity value of from 0 to 25%, the pixels actually turned on or rendered will be restricted to only one of the partitions or passes. If the tonal intensity value of the image is between 26% to 50% the pixels actually turned on or rendered will be restricted to only two of the partitions or passes. If the tonal intensity value of the image is between 51% to 75% the pixels actually turned on or rendered will be restricted to only three of the partitions or passes. If the tonal intensity value of the image between 76% and 100%, the image is clearly a shadow, and the minority white or non-printed pixels will be restricted to a minimum number of partitions or passes, the fourth partition or last pass.

[049] An alternate embodiment of the invention can provide an even more pleasing pixel

arrangement in the rendered image by blending some of the pixels turned on to render a tone into other partitions, or passes, rather than strictly adhering to restricting all the pixels turned on to render the tone to the minimum number of passes. In the two-pass example above, some of the rendered pixels for an image having a tonal intensity value of 25% may be kept or placed in the second partition *S2*. However, a substantial majority of the pixels turned on to render a tone will still be restricted to the minimum number of passes required to produce the tone. The substantial majority can be approximately 75% or more, and more preferably approximately 90% or more, of the pixels required to produce the tone.

[050] For comparison, FIG. 8 illustrates a halftone output pattern **44** generated using the pixel turn-on sequence **20** shown in FIG. 2. The halftone output pattern **44** does not restrict a substantial majority of the on pixels **46** to a single partition and is therefore more sensitive to inter-pass mis-registration.

[051] Another alternate embodiment includes generating a stochastic screen directly based on a constraint which enforces a restriction to one of the partitions in the highlights and the shadows and an unconstrained design in the remaining regions of the tone scale. This can be realized by optimizing the merit function for the single overall screen turn-on sequence, with explicit constraints in the optimization process to restrict a substantial majority of the black pixels in the highlights to a minimum number of partitions and correspondingly restricting a majority of the white pixels in the shadows to a minimum number of partitions.

[052] Still another embodiment of the present invention includes using error diffusion halftoning to turn on the proper pixels, on a pixel-by-

pixel basis, to render the image. An example of the invention using two partitions, such as the checkerboard partition **10**, includes adding a bi-level zero mean bias "image" signal which takes a positive value +D over one partition and a negative value -D over the other partition. The bi-level zero mean bias value can be added to either the thresholds or the input image as described below. For the case of the common checkerboard partition **10** shown in FIG. 1, the zero mean bias signal D is shown graphically in FIG. 9.

[053] A value of D between 32 and 64 has been found to provide satisfactory results when added to the input image having 256 possible tonal values. The value of D controls the degree to which the minority pixels are coerced towards, or restricted to, a single partition. The value of D can be scaled to suit input images having a lower or higher number of tonal values. Adding the zero mean bias signal in this manner causes a substantial majority, as defined above, of the pixels turned on to render a tone to be restricted to the minimum number of passes required to produce the tone. The zero mean bias signal causes a majority of the minority black pixels in the highlights to be localized to one of the partitions and a majority of the minority white pixels in the shadows to be localized to another one of the partitions. Since the added "image" signal is zero mean bias, the added signal does not influence the overall tone scale.

[054] Referring to FIG. 10, the method of halftoning using error diffusion in which the zero mean signal is added to the input tone value is shown. The method includes providing an input image having a plurality of pixels, each having an input tone value. The input image partitioned into the appropriate number and

arrangement of partitions, in this example a checkerboard partition is used although any suitable known number and arrangement of partitions can be used. Each input image pixel is processed and the zero mean bias image signal is added to the current pixel being processed based on which partition the pixel has been assigned. The zero mean bias signal, shown as b(x,y) is positive, that is +D, for one of the partitions and negative, that is -D, for the other. The error diffused from the previously processed pixels e(x,y) is also added to achieve the desired value for the current pixel d(x,y).

[055] The desired pixel value d(x,y) is then compared to a fixed threshold T, with T=127 in this example. If the desired value d(x,y) is greater than a fixed threshold T, the output value for the current pixel o(x,y) is set to 255 and turned on, otherwise the output o(x,y) is set to 0 and not turned on. The output value o(x,y) is subtracted from the desired value for the current pixel d(x,y) to provide an error value for the current pixel z(x,y) which is diffused to pixels yet to be processed in a known manner.

[056] Yet another embodiment of the invention using error diffusion is illustrated in FIG. 11. The method is similar to the previously described method of error diffusion, except that the zero mean bias signal b(x,y) is added to the threshold values based on which partition the current pixel being processed has been assigned. In effect, the threshold values are also partitioned in a manner similar to the input image pixels, as shown graphically in FIG. 9. Positive values of the zero mean bias signal, that is +D, are added to each threshold value corresponding to one partition **124a** and negative values, that is -D, are added to each threshold value corresponding to the other partition **124b**. The

fixed threshold value T0, is 127 in the present example, which is approximately 50% of the possible 256 input tone values, however, any suitable known threshold value can be used.

[057] In the example for a checkerboard partition arrangement illustrated generally at **50** in FIG. 12, the zero mean bias signal +D and -D, also shown as b(x,y) in FIG. 11, is 32. The threshold values in the first partition, where T(x,y)=T0+b(x,y)=127+32=159 is used for elements 224a and the threshold values in the other partition, where T(x,y)=T0+b (x,y)=127+(-32)=95 is used for elements **224b**.

[058] If the desired value d(x,y) is greater than the threshold T(x,y), the output value for the current pixel o(x,y) is set to 255 and turned on, otherwise the output o(x,y) is set to 0 and not turned on. The output value o(x,y) is subtracted from the desired value for the current pixel d(x,y) to provide an error value for the current pixel z(x,y) which is diffused to pixels yet to be processed in a known manner.

[059] The invention can also be readily applied to the printing of color images. The invention can be used on a separation by separation basis for each color separation using any known halftoning method including those described above. Other examples of color halftoning methods generating screens which can be re-ordered to reduce the effects of multi-pass mis-registration include, but are not limited to, vector methods for stochastic color screening as described in Pending U.S. Patent Application Serial Number 09/602,746, filed June 23, 2000 which is hereby incorporated by reference herein.

[060] Further, the error diffusion methods described above can be combined with any other known

methods of error diffusion, including but not limited to the sum-and-difference or semi-vector techniques for error diffusion disclosed in U.S. Patents 6,072,591 and 6,014,233 which are hereby incorporated by reference herein.

[061] Referring to FIG. 13, the invention also includes a system for multi-pass rendering shown generally at **200**. An input image, as described above, forming an electronic representation of an original document is directed to an image processing unit (IPU) **204** to be processed. The IPU **204** produces an output image rendering suitable for printing on a multi-pass printer **208**. The IPU **204** includes a halftone generator **210** including means for restricting a substantial majority, as defined above, of the pixels turned on to render a tone to the minimum number of passes required to produce the tone in a variety of manners as described above.

[062] In one embodiment, the halftone generator **210** can be a halftone screen generator including a stochastic screen pixel turn-on sequence generator for creating a stochastic screen pixel turn-on sequence in the manner described above, and means for partitioning the stochastic screen pixel turn-on sequence into a plurality of partitions as described above. The restricting means includes means for re-ordering the stochastic screen pixel turn-on sequence to restrict a substantial majority, as defined above, of the pixels turned on to render a tone to the minimum number of passes required to produce the tone in a manner described above.

[063] In another embodiment, the halftone generator **210** can generate the halftones using error diffusion as described above. The halftone generator **210** can include means for partitioning the input image into a plurality of partitioned pixel tone values in a manner

described above, means for processing the partitioned pixel tone values to produce a previously processed pixel error diffusion value in a manner described above.

[064] The halftone generator **210** can also include means for processing a current partitioned input pixel tone value including means for adding the previously processed pixel error diffusion value to the current partitioned input pixel tone value to achieve a desired pixel value in the manner described above, and means for comparing the desired pixel value with a threshold value to produce an output signal for rendering the image in the manner described above. The restricting means can include means for adding a zero mean bias signal to the current partitioned input pixel tone value, where the zero mean bias signal is based on the partition containing the partitioned pixel tone value as described above.

[065] In an alternate embodiment the restricting means includes means for adding a zero mean bias signal to the threshold value, rather than the input pixel tone value, where zero mean bias signal is based on the partition containing the partitioned pixel tone value as described above.

[066] The invention has been described with reference to preferred embodiments. Obviously, modifications and alterations will occur to others upon reading and understanding the preceding specification. It is intended that the invention be construed as including all such modifications and alterations insofar as they come within the scope of the appended claims or the equivalents thereof.